A 90 GHz array for the Green Bank Telescope

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Abstract

We report on the design and construction of an 8×8 bolometer array designed to operate at 90 GHz on the new 100 m Green Bank Telescope (GBT). The bolometers are Transition Edge Superconducting (TES) detectors read out using a SQUID multiplexing system. The receiver will be one of the first astronomical instruments to use such detectors. To cool the detectors, we have developed ^{3}He and ^{4}He sorption refrigerators that cycle from a two-stage pulse-tube cryocooler. The system has been demonstrated to be robust, to be capable of cycling autonomously, and to provide 15 μW of cooling below 286 mK with a hold time over 70 h. Although modest in size, a combination of the size of GBT and the low noise of the TES detectors will make our receiver one of the most sensitive of its kind.
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1. Introduction

For many years bolometers have been the most sensitive detectors for mm-wave telescopes, but until recently sensitivity was limited by detector noise. We are building an 8×8 element 86–94 GHz array which will become a facility instrument on the Green Bank Telescope (GBT). We will be using the Transition Edge Superconducting (TES) bolometers being developed by Benford et al. [1]. A combination of the size of the GBT and the low noise of the TES bolometers mean that NEPs of each detector will be largely background limited.

2. The Green Bank Telescope

The GBT [2] is 100 m in diameter and is designed for frequencies up to 100 GHz. The telescope has an off-axis Gregorian design and multi-frequency capability with up to 8 receivers being housed in a rotating carousel at the secondary focus. By rotating the carousel, the operating frequency can be changed without any downtime. The 90 GHz array will be placed at one of these locations. At 90 GHz the GBT will have a beam size of 8 arcs.

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3. Cryogenics

3.1. Requirements

To cool the detectors a cryogenic system with the following properties was needed:

- The system must provide 15 μW of cooling at temperatures below 290 mK. This must be maintained at angles of at least 57° from the vertical (corresponding to observations 20° above the horizon).
- When the receiver is not in use it may be tipped by up to 72° in any direction. After this it must be ready to use within 90 min of being returned upright.
- A minimum hold time of 24 h, to allow deep observations, and a goal of 68 h, to allow for flexible scheduling of the telescope, is required.
- The receiver must be operated remotely by members of the astronomical community who are not familiar with cryogenics.
- So as not to affect the bolometers, low mechanical vibrations and moderate temperature stability are needed.

3.2. Closed cycled cooling to 250 mK

Due to the remote operation requirement, expendable liquid cryogens were ruled out. Instead, we use a two stage pulse tube cryocooler to cool the condenser of a ^{4}He sorption refrigerator which is in turn used to cool the condenser of a ^{3}He sorption refrigerator (Fig. 1) [3]. This system has temperature stages of 40.5 K (pulse tube first stage), 2.7 K (pulse tube second stage), 0.7 K (^{4}He refrigerator) and 0.250 K (^{3}He refrigerator—unloaded). With a load of 15 μW the ^{3}He refrigerator runs at 270 mK and has a hold time of 72.7 h. This temperature was stable to 0.09 mK on time-scales from 1 s to 10 min. After initial cooling, long-term drifts dropped below 0.2 mK/h.

The cycling of the refrigerators is computer controlled, occurring on demand or autonomously when the ^{3}He refrigerator runs out. Typically it takes 4.5 h from the start of a cycle to when the ^{3}He refrigerator is stable below 0.290 mK. Cycling time is dominated by the limit in the cooling power
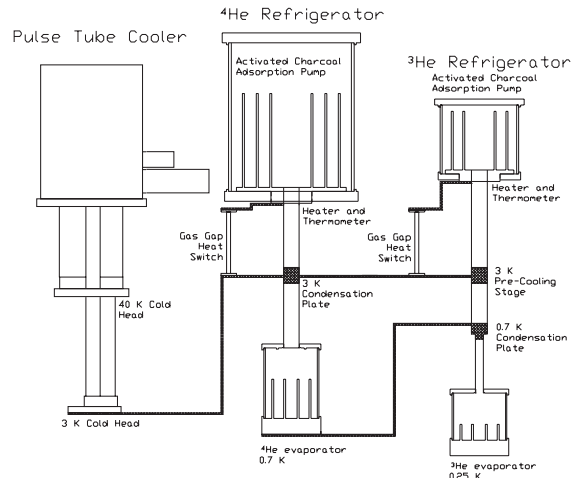

Fig. 1. A schematic diagram of the closed cycle cryogenic system. Parts are not to scale.

of the pulse tube. Cycling has been shown to be effective at tilts up to at least 45° from the vertical.

The pulse tube is designed to operate vertically. When it is tipped more than 30° it looses cooling capacity. Tipping the system to 57° from the vertical resulted in the first stage warming up to 70 K in 2 h. The second stage was relatively unaffected showing only a rapid warming to 3.4 K before becoming stable. Both the ^{3}He and ^{4}He stages were unaffected. On tilting the system to 72° the second stage of the pulse tube warms to 20 K in an hour and the charcoal pumps stop working, however the system recovered within 40 min of being returned to vertical. With this last test we were able to conclude that our cryogenic system would meet all our needs on the GBT.

4. The TES array

Because our array size is 8×8 then there is no need to use the pop-up technology being developed for larger arrays [1]. Our detectors will be made on a single planar wafer and all connections to the devices will come out along the supporting structures which are 0.3 mm wide. The adsorbers will be 2.9 mm square and the spacing of the detectors will be 3.3 mm. The saturation power of the devices will be 8 pW and we expect the time

constant to 5 ms. Eight SQUID multiplexers will be used to read the detectors out.

5. The optics

Previous bolometer arrays such as SCUBA [4] have had beams spaced by 2 resolution elements ($2f\lambda$) on the sky. Due to $1/f$ noise, missing data must be filled in as quickly as possible using complex scan strategies. This is often accomplished using the secondary or tertiary optics of a telescope to chop the beams on the sky.

There is no easy fast way to chop the GBT. By using a fully sampled array with pixels spaced by $0.5f\lambda$ on the sky maps can be made in a single scan and no fast chopping is needed. To get beams this close, feed horns cannot be used above our array. We also note the 90 GHz feedhorns are expensive and difficult to manufacture.

Instead illumination of the detectors is controlled using two aspheric silicon lenses with a cold Lyot stop between them (Fig. 2). The bandpass is defined using reflecting capacitive mesh filters. The Lyot stop controls stray light and, along with filter 3, it limits the amount of power incident on each detector. Everything inside the Lyot stop is cooled to either 2.7 or 0.270 K. Power landing on the detectors comes from two main directions; through the Lyot stop (which is a sum of emission from the telescope, the atmosphere and the astronomical signal) and the 2.7 K structure around the Lyot stop (which is reduced to acceptable levels by bandpass filter 3). When all sources of power are added up, the telescope's optics (warm and cold) will contribute 0.7 pW per detector. The atmosphere should contribute 0.5–2.8 pW (depending on weather) to give a total of 1.2–3.5 pW. Given the low intrinsic noise from the detectors, the receiver noise should be limited by the atmosphere to 1.2×10^{-17} W$\sqrt{s}$ corresponding to a sensitivity on the sky of 500–730 μJy$\sqrt{s}$/detector.
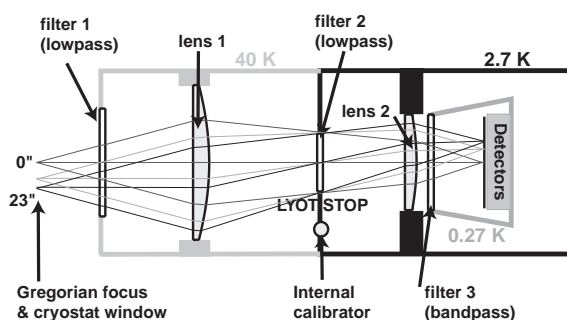

Fig. 2. The optics. Two anti-reflective coated, silicon lenses refocus the light and a Lyot stop controls the illumination of the telescope. Filter 3 defines the bandpass (86–94 GHz) and also controls the loading on the detectors. Filters 1 & 2 are low-pass filters which block leaks in the bandpass filter and control the loading on the cryogenics.

6. Conclusions

In 6 h the 90 GHz array on the GBT will be able to map a $5' \times 5'$ area of sky to 40 μJy per 8 arcs beam. This compares to 7 mJy for Nobeyama telescope (90 GHz, 2–6 arcs beam) and 1 mJy for bolocam on the LMT (225 GHz, 8 arcs beam). The receiver makes use of a new closed cycle cryogenic system and it will be one of the first to use TES detector arrays for astronomy. Future upgrades include expanding the bandpass or the size of the array.

References

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